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OPTIMUM DIGITAL DATA STORAGE ON MAGNETIC TAPE.(U)

DEC 79 E L LAW, W R HEDEMAN

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In recent years considerable effort has been expended on high density digital recording. The goal has been to increase the data storage per unit length of tape, usually focused on a fixed track width. The present investigation advances the thesis that optimum data storage per square of tape is achieved by increasing the number of tracks, rather than the storage per track. An experimental method for the determination of the best operating point is described, and data is presented for Non-Return-to-Zero-Level (NRZ-L), Manchester and Miller codes for an ideal tape recorder, and also for an actual tape recorder.

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TABLE OF CONTENTS

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NOMENCLATURE

dB	Decibels
Hz	Hertz
ips	inches per second
IRIG	Inter-Range Instrumentation Group
kbps	Kilobits per second
kbpi	Kilobits per inch
kHz	Kilohertz
M	SNR Margin
Mbps	Megabits per second
N	Number of tracks
N_o	Original number of tracks
NRZ-L	Non-Return-to-Zero-Level
PCM	Pulse Code Modulation
R	Data rate
R_o	Original data rate
SNR	Signal-to-Noise power ratio

TP-80-03
December 1979

PACIFIC MISSILE TEST CENTER
Point Mugu, California 93042

OPTIMUM DIGITAL DATA STORAGE OF MAGNETIC TAPE

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SUMMARY

In recent years considerable effort has been expended on high density digital recording. The goal has been to increase the data storage per unit length of tape, usually focused on a fixed track width. The present investigation advances the thesis that optimum data storage per square of tape is achieved by increasing the number of tracks, rather than the storage per track. An experimental method for the determination of the best operating point is described, and data is presented for Non-Return-to-Zero-Level (NRZ-L), Manchester and Miller codes for an ideal tape recorder, and also for an actual tape recorder.

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INTRODUCTION

In recent years considerable effort has been expended on high density digital recording. The goal has been to increase the data storage per unit length of tape, usually focused on a fixed track width. The present investigation advances the thesis that optimum data storage per square of tape is achieved by increasing the number of tracks, rather than the storage per track. An experimental method for the determination of the best operating point is described, and data is presented for Non-Return-to-Zero-Level (NRZ-L), Manchester and Miller codes for an ideal tape recorder, and also for an actual tape recorder.

THEORY

An instrumentation tape recorder can be modeled as a communication link with fixed bandwidth and constant noise power at any tape speed, since the dominant noise source, even for track width of 0.050 inch, is the first circuit of the reproduce amplifier. Assume that, for some fortuitous reason, signal-to-noise margin becomes available and the data rate in the link may be increased to restore the bit error probability to its original value. What increase in data rate should be observed? Though the question cannot be answered in the absolute sense it is possible to describe the *best* result that *might* be observed.

The signal voltage at the output of a tape recorder is proportional to the width of the track. The signal-to-noise power ratio (SNR) is proportional to the square of the width of the track. Available margin, M dB, can be exploited to increase the number of tracks, N, returning each of the resulting links to those signal and noise conditions present in the original link. The ratio of N to N_0, the original number of tracks, is:

$$\log(N/N_0) = M/20 \qquad (1)$$

We assume that the data rate in the assembly of links is proportional to the number of tracks. Then the ratio of the data rate, R, to the original data rate, R_0, is:

$$\log(R/R_0) = M/20 \qquad (2)$$

Then, in a communication link involving a tape recorder, if using the available margin, M, to increase the packing density per track yields a result less than that described by equation (2), we can increase the number of tracks and obtain a better result. In effect, the data storage per square of tape is optimized. For actual or simulated tape recorder, if we plot log (data rate) as ordinate and SNR, dB, as abscissa for a constant bit error probability, when the slope is greater than an octave of data rate for 6 dB of margin the packing density on the track should be increased; when the slope is less the track width should be decreased.

An actual recorder might not realize this theoretical increase, since narrower tracks are more prone to tape "tracking" dynamic problems. Smaller tape imperfections become more important, affecting the dropout characteristics of the emulsion itself.

An interesting result of equation (2) is that it is possible to assess overhead data, such as parity, in terms of margin in the link. And it is also possible to assess code bit detection losses in terms of data rate.

TEST CONFIGURATION

The test configuration is shown in figure 1. An idealized tape recorder was simulated by passing the Pulse Code Modulation (PCM) data through a 400 Hz to 500 kHz Bessel bandpass filter and summing the filtered data with spectrally conditioned Gaussian noise (see figure 1), which matched the noise spectrum of a tape recorder running at 30 ips. The terminal slopes of the bandpass filter were 24 dB per octave. Spectral conditioning is performed by the passive filter network at the input to the summing amplifier. The noise spectral density is shown in figure 2. The attenuator allowed the noise to be changed in 1 dB steps. The SNR was calibrated as follows:

1. A 2047-bit pseudo random sequence at 100 kbps was generated. Noise was removed from the summing amplifier and the PCM signal was measured using a true root mean square digital voltmeter.

2. The PCM signal was removed, and the noise attenuator was set to 0 dB. The noise was filtered by a filter with an equivalent noise power bandwidth of 500 kHz. The rms of the noise was then set equal to the rms of the PCM signal.

Therefore, the SNR used in this report is equal to the rms signal out of the bandpass filter divided by the noise in the 500 kHz bandwidth. This is equivalent to the definition of SNR for analog magnetic tape recorders in Inter-Range Instrumentation Group (IRIG) Document 118-75.

For some tests a wideband, group 2, tape recorder replaced the simulator. SNR was varied by changing the record level at the input to the record amplifier, in all cases using a level less than the standard record level as defined in IRIG 106-77. Output power was maintained constant, within 2 dB, by manual gain control of the reproduce amplifier in order to minimize stress on the bit detector.

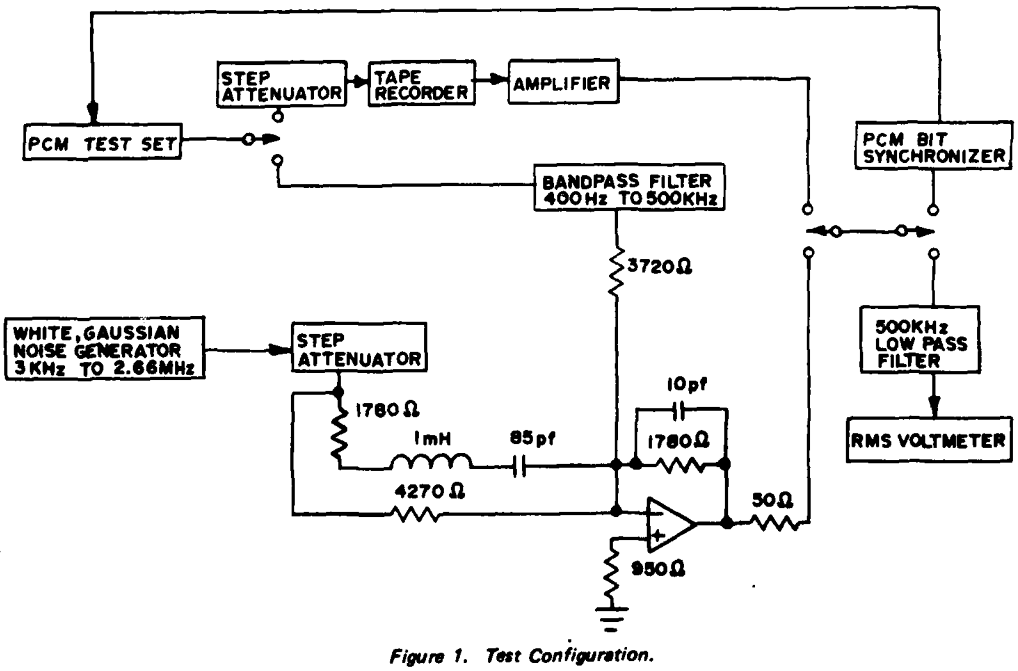

Figure 1. Test Configuration.

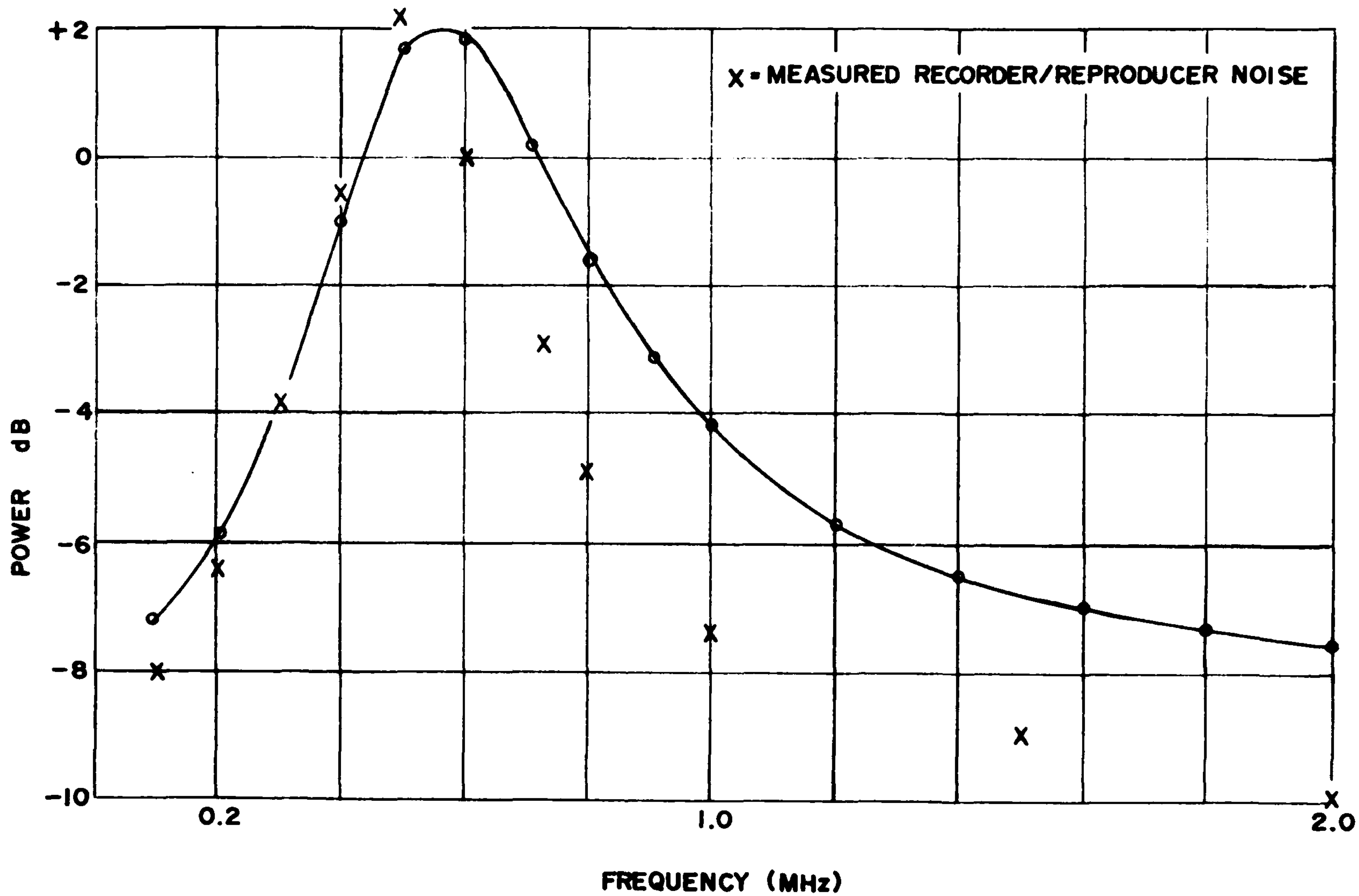

Figure 2. Noise Power Spectral Density at Input to PCM Bit Synchronizer.

TEST RESULTS

Tests were performed using NRZ-L, Miller and Manchester codes with a 2047-bit pseudo random pattern at data rates from 100 kbps to more than 1 Mbps. A good commercial bit synchronizer, with dc restoration, was used. SNR was varied until the BEP was 10^{-6} at each data rate.

Experimental data, figure 3, shows log (data rate) vs SNR, dB, for a fixed bit error probability for the three codes used. For each code there are two definite operating regions. At low values of SNR the link is noise limited, and at high values of SNR the link is band limited. In the noise limited region a margin increase of 6 dB would support an octave increase in packing density or data rate and as long as this slope persists it is proper to increase the packing density. (The fact that this slope is the same as that due to increasing the number of tracks is a coincidence). In the band limited region much more than 6 dB of margin is required to support an octave increase in data rate; it is clearly unprofitable to operate in this region. The operating point should be the packing density beyond which more than 6 dB of additional SNR is required to double the data rate (a tangent point).

The data for the Miller code and NRZ-L in the noise limited region shows the Miller code data rate to be approximately 0.6 of the NRZ-L data rate for the same SNR. This is nearly the Miller code data rate predicted by equation (2) due to the 3.5 dB decoding loss relative to NRZ-L. This loss is inherent in the Miller code and cannot be recovered using the optimum recorder.

The Manchester code remains in the band limited region to lower values of SNR than either Miller or NRZ-L codes. From the simulator results one would conclude that data storage per square with the Manchester code would be nearly the same as that with NRZ-L, and greater than storage with the Miller code, if the number of tracks was twice the optimum number with the NRZ-L code.

For eight bit odd parity NRZ-L the equivalent margin penalty is 1.16 dB. Error multiplication in decoding randomized NRZ-L results in a margin penalty of 0.5 dB, or an equivalent information rate of 0.94 of the NRZ-L data rate for random data.

At low data rates, less than 200 kbps, the NRZ-L code data shows a reverse slope of log (data rate) vs SNR. This is due to untracked baseline wander in the bit detector, which degrades performance. It becomes very difficult to track baseline wander at low values of SNR.

Actual tape recorder data are shown in figure 4. The band limited region is reached at a much lower value of SNR than with the simulator. This is probably due to the fact that the recorder cut-off slope is much steeper than the Bessel filter because of the reproduce gap length effect. The Manchester code is less efficient than NRZ-L, but this may be due to a "spike" in the noise spectrum that assumes greater importance at low values of SNR.

The recorder data shows a tangent point, for NRZ-L, at an SNR of approximately 11.5 dB and a packing density of 20 kbpi, while the SNR required for a packing density of 33 kbpi was 22.5 dB. If the 11 dB of margin was used to increase the number of tracks by a factor of 3.5, data storage per square would be twice that obtained from increasing the storage per track.

The theory presented here is based on the assumption that, in the limit, as the track width becomes very small, post amplifier noise becomes dominant. Measurements of the noise power spectrum of several tracks of the actual recorder, and the ratio of noise power with tape moving and static show, that on the average, tape noise is about equal to post amplifier noise. This being the case, as track width is decreased noise will decrease, and the increase in number of tracks predicted by equation (2) is less than should be used.

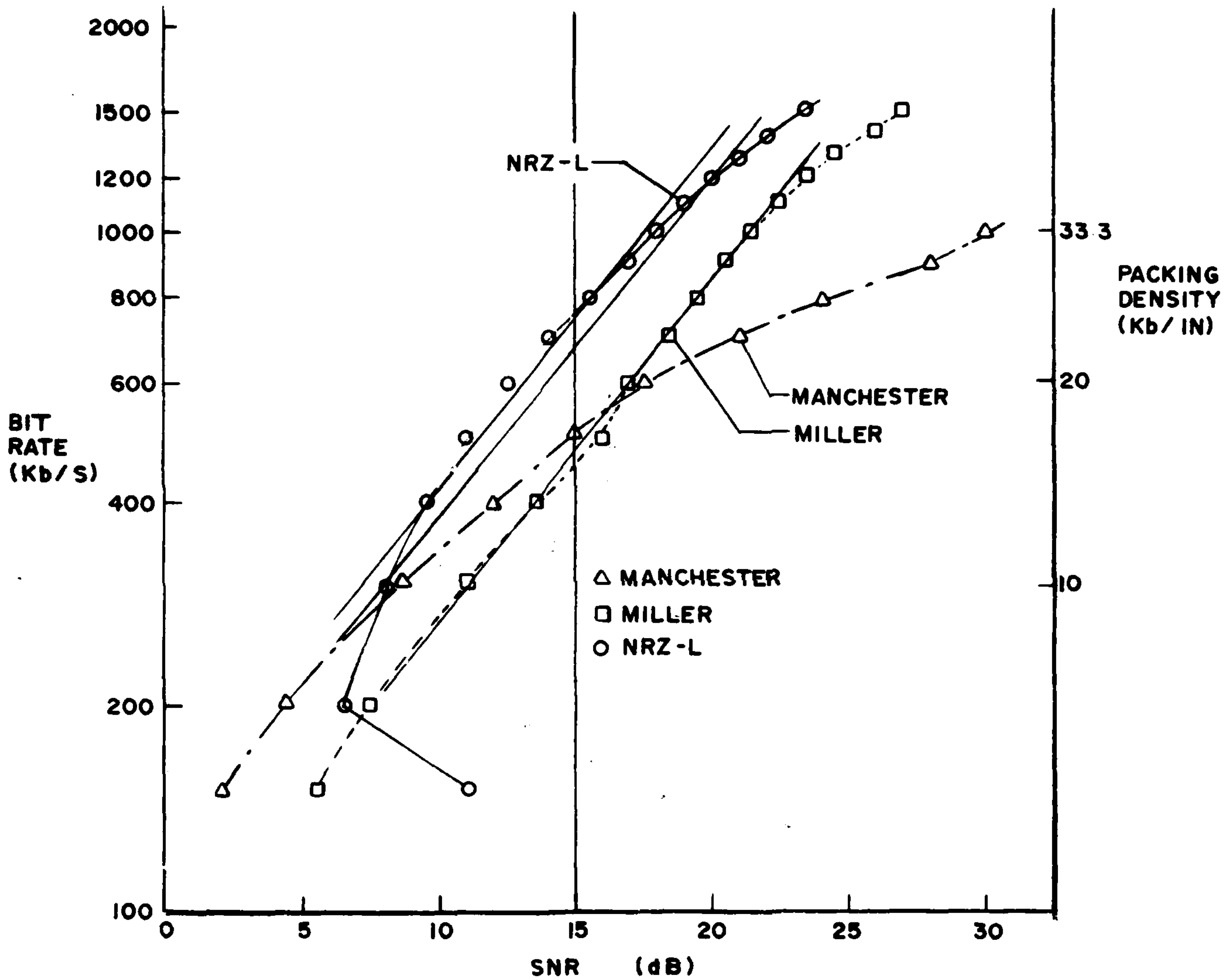

Figure 3. Bit Rate vs SNR for 10^{-6} BEP (Simulated Tape Recorder).

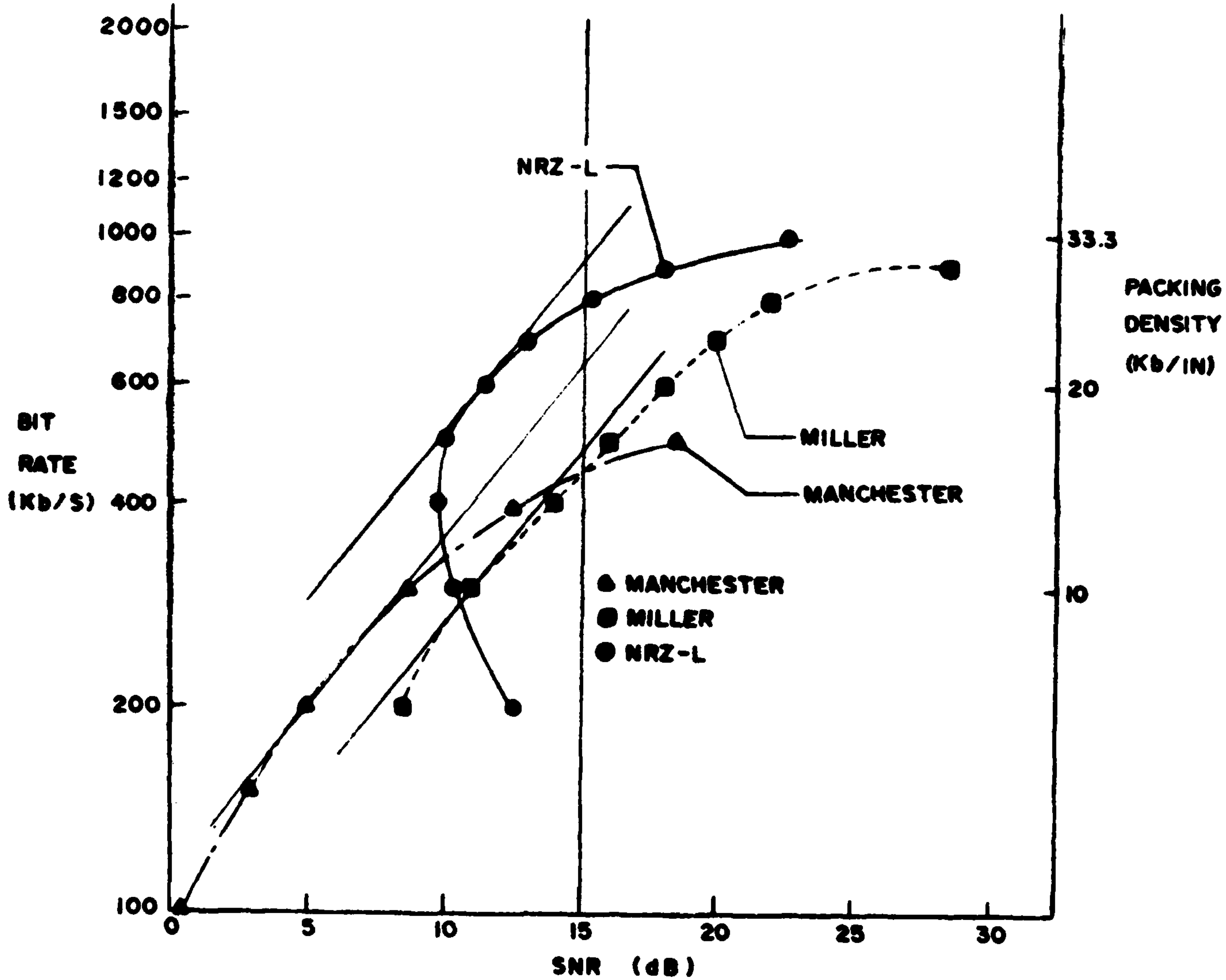

Figure 4. Bit Rate vs SNR for 10^{-4} BEP (Actual Tape Recorder, 30 ips).

CONCLUSIONS

The most effective use of magnetic tape for the storage of digital data is attained when the number of tracks of the recorder is tailored to the code used, the desired bit error probability, overhead requirements of the code, etc. The optimum storage per square of tape is achieved when operating in the noise limited region of the recorder. The optimum track width is that which yields the SNR required to attain the maximum packing density in the noise limited region at the desired bit error probability.

Current attempts to improve the storage of digital data largely result in operation in the band limited region, and represent less than the best management of available signal-to-noise margins. Also, differences in data storage due to code characteristics are obscured, making the choice of a code, from those available, somewhat indifferent.

Further improvements in code efficiency, as by convolutional codes, will provide additional margins by permitting operation at a lower value of SNR. The greatest benefits of these improvements, as far as digital data storage is concerened, can only be realized by increasing the number of tracks of the recorder. Using these, and other advanced techniques, it seems entirely possible that data storage of 10^{-7} bits per square inch of tape can be accomplished — nearly an order of magnitude better than best current practice.

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